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TITLE: DEUTERON FORWARD PHOTODISINTEGRATION: MESON CURRENTS AND RELATIVITY

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DEUTERON FORWARD PHOTODISINTEGRATION: MESON CURRENTS AND RELATIVITY

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ABSTRACT

The few-nucleon problem in nuclear physics and the few-electron problem in atomic physics are shown to possess similarities. Relativistic aspects of the latter are reviewed. The radiative decay of the $^3P_1$ excited state of helium-like ions to the $^1S_0$ ground state is shown to be a theoretical analogue of low-energy deuteron forward photodisintegration. Both have large relativistic components. The extended Siegert's theorem, which permits application of Siegert's technique to arbitrary photon wave lengths, is applied to both transitions. Physical arguments for the two processes are stressed, and the relevance of interaction currents is discussed.

Nuclear and atomic physics have many similarities. Nowhere are these similarities more apparent than in the few-body problem, which is a special field in both disciplines. I am not an expert in the atomic field; rather I am a dilettante. Most of my dabblings have been in the hydrogenic atom[1] and two-electron atom problems.[2] Although I clearly run the risk of giving a distorted impression of atomic physics, let me remark that if what I say isn't true, it should be!

The few-body problems of any field are those areas where computational expertise is greatest, and where new ideas can be most easily tested and the underlying tenets given their most severe challenges. The difficulties inherent in any attempt to solve the many-body problem make tests of fine theoretical details extremely dubious in such systems. Hence the attention given to simple systems.

The traditional aspects of these fields are the tacit assumptions made in most calculations, assumptions which are invariably made because they simplify without a significant loss of accuracy. I have listed below what I consider to be traditional aspects of nuclear physics and the corresponding aspects of atomic physics.

Traditional Aspects

Nuclear Physics	Atomic Physics
(a) Nonrelativistic nucleons	(a) Nonrelativistic electrons
(b) Two-nucleon forces	(b) Two-electron forces
(c) No meson degrees of freedom; no excited nucleons; no quark substructure	(c) No self-radiative effects; no virtual photons; point nuclei only

I do not mean to imply that these aspects have never been challenged--far from it. Relativistic treatments of the atomic one-electron bound states predate[3] the Schrödinger and Dirac equations. Nearly fifty years ago 3-body forces were derived for both electrons and nucleons.[4] Retardation in photon exchange was considered at nearly the same time.[5] Nevertheless, with the exception of the few-electron problem, the tradition has been to treat atoms as composed of nonrelativistic electrons interacting via the two-body static Coulomb force.

The situation in nuclear physics is somewhat different qualitatively from atomic physics. In the latter field the interaction is known and most of the attention is directed at detailed treatments of wave functions; the sophistication is very impressive. In nuclear physics only pion exchange has any credible fundamentality because of the primitive nature of QCD calculations and because the older meson-exchange mechanism is phenomenological. In addition, light atoms have many bound states, while the few-nucleon systems have only one, or none. The atomic few-electron problem must be examined[6] in order to appreciate its richness and elegance.

To the best of my knowledge no experimental evidence exists for three-electron forces; these forces are of order $(v/c)^4$, second-order relativistic corrections, and correspondingly small. The evidence for three-nucleon forces is circumstantial.[7,8] There is a binding defect of approximately 1 MeV in the three-nucleon bound states for a wide variety of realistic nucleon-nucleon forces. Certain three-body forces generate additional binding of approximately that amount. This is a topic with intense current interest, and one I almost lectured on here. Excellent evidence now exists[8] for aspect (c) in nuclear physics. The field of meson-exchange currents had a long adolescence but has now come of age.

Although our attention will be directed at deuteron photodisintegration, we will begin by examining relativistic corrections in the few-electron problem. I have chosen this procedure for three reasons: (1) It is interesting to indulge in "cultural exchange" with other fields; (2) The physics of one particular two-electron atom process is immediately applicable to the deuteron; the former has been tested experimentally, and no one will doubt the results; (3) Much of the experimental work on few-electron ions with large Z (proton number) is now performed at heavy ion machines, which are nuclear physics facilities. I hope you find this approach interesting.

Figure 1 shows schematically the low-lying levels of hydrogenic atoms. The M1 radiative transition between the 2s and 1s states is dominated by relativistic corrections,[6] because the magnetic moment operator is the sum of spin and orbital angular momentum operators. The latter vanishes for s-states, while the former does not contain any radial factors which destroy the orthogonality of the radial wave functions of the two states. The retardation effect of the finite photon wavelength, the Lorentz contraction of the magnetic moment, and a contribution from the spin-orbit interaction make comparable contributions to the transition.[9] The latter includes an interaction-current term (one-photon-exchange) whose strength can be altered by means of unitary transformations. This is an example of the kind of "ambiguity" which often arises in processes of relativistic order.

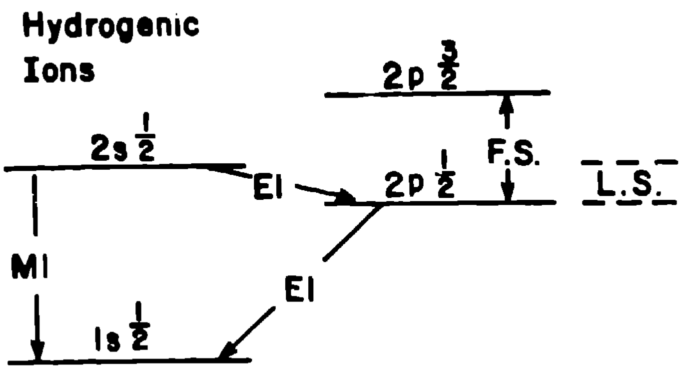

Fig. 1. Low-lying levels of hydrogenic ions.

More familiar to most physicists are the $2s_{1/2} \to 2p_{1/2}$ transition and the 2p fine-structure splitting. The former is the quintessential example of an exception to category (c) of traditional aspects. The $2s_{1/2}$ state is normally degenerate with the $2p_{1/2}$ state. Self-radiative effects (the Lamb shift) and to a lesser extent the vacuum polarization raise the $2s_{1/2}$ level slightly. The effect is very small, but by generating a transition between the two levels the normal Bohr component of the energies does not enter. In spite of the complexity of the physics which determines the energy shift,[10] the electric dipole transition is very simply calculated if one uses the Siegert form[11] of the electromagnetic current, $\vec{J}(\underset{\sim}{x})$, which couples the atom to the radiating photon. Siegert showed that the long wavelength part of the current operator for dipole transitions could be rewritten as

$$\vec{J}(0) = \int d^3x\, \vec{J}(\underset{\sim}{x}) = -\int d^3x\, \vec{x}\, \vec{\nabla}\cdot\vec{J}(\underset{\sim}{x}) = i[H,\vec{D}] \ , \tag{1}$$

where $\vec{D} = \int \vec{x}\, \rho(\underset{\sim}{x})$,

$$\vec{J}(\underset{\sim}{q}) = \int d^3x\, e^{i\underset{\sim}{q}\cdot\underset{\sim}{x}}\, \vec{J}(\underset{\sim}{x}) \ , \tag{2}$$

and

$$\vec{\nabla}\cdot\vec{J}(\underset{\sim}{x}) = -i[H,\rho(\underset{\sim}{x})] \ , \tag{3}$$

for a photon whose momentum $\underset{\sim}{q}$ is negligibly small. The key ingredient in rewriting the current in terms of the Hamiltonian, H, the electric dipole operator, $\vec{D}$, and the charge density, $\rho(\underset{\sim}{x})$, is current continuity given by eqn. (3), which has impeccable credentials. The relationship (1) is actually quite old, dating back to Schrödinger's calculation[12] of the electric dipole transitions between Stark-shifted states -- the first modern calculation of a quantum transition. Schrödinger actually assumed eqn. (1) because it held classically, and later proved current continuity for his equation in the presence of "ordinary" forces. An explicit demonstration of eqn. (1) for the Lamb shift is fairly recent.[10] Although the current and Hamiltonian are <u>very</u> complicated in that case, $\rho(\underset{\sim}{x})$ is not, and transition matrix elements are trivial to calculate using eqn. (1).

Siegert's result is called "Siegert's theorem" and forms the backbone of the photonuclear field. The name is a misnomer, because the "theorem" is actually an approximation. Although eqn. (1) is exact, using the nonrelativistic dipole operator $\vec{D}_o$ in place of $\vec{D}$, as advocated by Siegert, is an approximation. Siegert showed that any correction to this prescription is of order $(1/c^2)$ and should be small. These corrections can be either potential dependent, $\Delta\vec{D}_V$, or momentum dependent, $\Delta\vec{D}_o$.

The best known example of a relativistic effect in an atom is the 2p3/2-2p½ fine structure, a knowledge of which predates quantum mechanics; it is shown in Figure 1. The Bohr contribution to the energy difference cancels, and the splitting is produced by the spin-orbit interaction, whose form is $H_{so} = - e_p \vec{E}\cdot\Delta\vec{D}_{so}$, where $\vec{E}$ is the electric field of the proton, e_p is the (positive) fundamental charge and

$$\Delta\vec{D}_{so} = - \frac{\hbar(2\mu-e)}{4m^2c^2} \vec{\sigma} \times \vec{p} , \qquad (4)$$

where μ, e, m, $\vec{\sigma}$, and $\vec{p}$ are the electron's magnetic moment (in magnetons), charge, mass, and spin and momentum operators. Note the explicit factor of $1/c^2$ (which won't be seen again); this is a relativistic correction. Two phenomena generate $\Delta\vec{D}_{so}$. One is the electric dipole moment generated when a magnetic moment $\vec{\mu}$ moves with velocity $\vec{v}$: $e\vec{v}\times\vec{\mu}/c$. This can also be viewed as the usual interaction in the electron's rest frame with the magnetic field generated by transforming the electric field from the proton's rest frame. In any event it generates the μ-term. The remaining e-term was explained by Thomas[13] at the same time Schrödinger was performing his seminal work. The electron's velocity vector is constantly changed by the acceleration, $\vec{a}$. To an observer on the proton the coordinate axes attached to the electron are rotating (precessing) with the Thomas frequency: $\vec{v}\times\vec{a}/2c^2$. This leads immediately to the e-term in eqn. (4).

The spin-orbit interaction's origin is kinematical, which explains its ubiquity. That was the reason for the exercise above. It occurs naturally in any derivation[14] of the nucleon-nucleon force when $1/c^2$-terms are kept. Two more examples of its occurrence in atomic physics are contained in Figure 2, which displays the low-lying states of helium-like ions, which have two electrons. The $^3S_1 \rightarrow {}^1S_0$ transition is similar to the $2s_{\frac{1}{2}} \rightarrow 1s_{\frac{1}{2}}$ transition in hydrogenic ions, because the magnetic moment operator cannot flip the spin of one electron relative to the other.[6] Retardation, Lorentz contraction of the M1 operator, and interaction currents generated by the minimal substitution in the momentum dependence in eqn. (4) ($\vec{p} \rightarrow \vec{p} - e\vec{A}$) drive the reaction.[9] Theory and experiment are in good agreement.[15]

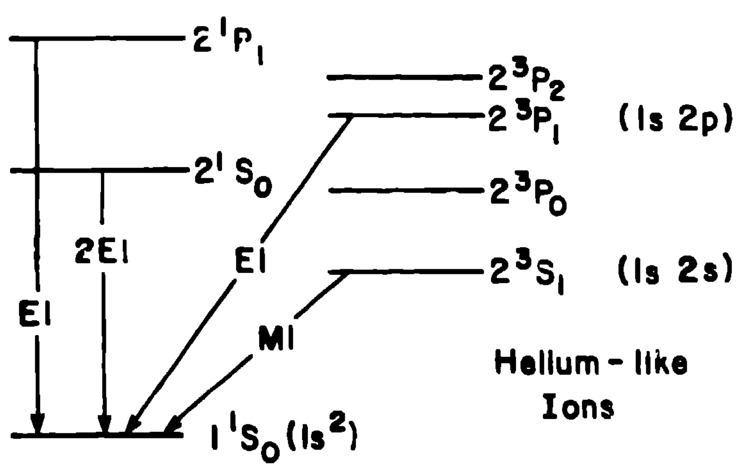

Fig. 2. Low-lying levels of helium-like ions.

More interesting perhaps and more relevant to our purposes is the $^3P_1 \rightarrow {}^1S_0$ electric dipole transition. This is called an intercombination line and occurs in the solar corona and is relevant to Tokamak fusion reactors. It also has astrophysical relevance. The transition is seen to be forbidden in first order if we use Siegert's form of the electric dipole current, and the form of the nonrelativistic dipole operator: $\vec{D}_0 = e\vec{r}$. This is spin independent and can't induce triplet to singlet transitions. How does the transition proceed, then? Part of the answer lies in the nonrelativistic assumption used above; we need to rescind Siegert's approximation. Clearly the spin-orbit dipole operator, $\Delta\vec{D}_{sp}$, contributes to $\vec{D}$ and can induce the transition. Retardation of the nonrelativistic electric operator can also contribute because the current contains a spin-magnetization term of the form: $-i(\vec{q}\times\vec{\sigma})\mu/2m$. In addition the electron spin-orbit potential admixes small amounts of $^1P_1$ state with the dominant $^3P_1$ part; this admixture is a relativistic component of the wave function.[15,16] The ordinary dipole operator can then connect the components with the same spin generated by the noncentral atomic forces.[16]

Our problem is to write the current in a form which manifests each of these processes.[2] Clearly a good starting point is eqn. (1), Siegert's theorem, but including the spin-orbit contribution to the dipole operator. A variety of formulae exist for including the effects of retardation; it is not clear that they build in current continuity, eqn. (3), in the maximal way. For this reason we will develop our own form. The reason for doing this is the complexity of the atomic force and current when $1/c^2$ corrections are included, and the relative simplicity of the charge density. Both the interaction and the corresponding current are quite messy! The key ingredient in our calculation is the Fourier transform of eqn. (3)

$$\vec{q}\cdot\vec{J}(\underset{\sim}{q}) = [H,\rho(\underset{\sim}{q})] \;, \tag{5}$$

where $\rho(\underset{\sim}{q})$ is the analogue of eqn. (2). Siegert's result is generated by expanding both sides of eqn. (5) to first order in $\vec{q}$ and equating coefficients. It is only because $\vec{q}$ is a variable that a constraint on the component of the current along a particular direction gives information on the complete current. Terms which are second order in $\vec{q}$ in eqn. (5) involve the electric quadrupole operator, so we examine the third-order terms in $\vec{q}$:

$$\int d^3x(x^\alpha x^\beta J^\gamma + x^\alpha x^\gamma J^\beta + x^\beta x^\gamma J^\alpha(\underset{\sim}{x})) = i[H, \int d^3x \;\; x^\alpha x^\beta x^\gamma \; \rho(\underset{\sim}{x})] \;. \tag{6}$$

This result is complicated by the obvious requirement that we keep track of 3 different Cartesian indices (α,β,γ), which connected to factors of the photon momentum, $\vec{q}$. There are two notable features of eqn. (6): (1) The right-hand side is the Cartesian octupole tensor; (2) The left-hand side involves only terms symmetric in the indices. The octupole tensor is reducible; that is, it contains a piece which is dipole in nature and can be obtained by contracting any two indices together:

$$\int d^3x \;(2\vec{x}\;\vec{x}\cdot\vec{J}(\underset{\sim}{x}) + x^2\;\vec{J}(\underset{\sim}{x})) = i[H, \int d^3x\;\vec{x}\;x^2\rho(\underset{\sim}{x})] \;. \tag{7}$$

This relationship contains the complete information we need on the current conservation constraint for electric dipole transitions. If we expand $\vec{J}(\underset{\sim}{q})$ to second order in $\vec{q}$, arrange indices on $\vec{x}$'s and $\vec{J}$'s so they are either symmetric or nonsymmetic in the indices, use of eqn. (7) results in

$$\vec{J}_{E1}(\underset{\sim}{q}) = i[H, \;\; \vec{D} - \frac{\overleftrightarrow{qq}\cdot\vec{O}}{10} + \frac{\vec{q}\times(\vec{q}\times\vec{O})}{30}] + \frac{\vec{q}\times(\vec{q}\times\vec{N})}{6} + \ldots \;, \tag{8}$$

where $\vec{O}$ is the integral on the right-hand side of eqn. (7), $\int d^3x\;\vec{x}\;x^2\rho(\underset{\sim}{x})$, and $\vec{N}$ is related to the magnetic density $\vec{\mu}(\underset{\sim}{x}) = \frac{1}{2}\vec{x}\times\vec{J}(\underset{\sim}{x})$:

$$\vec{N}(\underset{\sim}{x}) = \int d^3x\;\vec{x}\times\vec{\mu}(\underset{\sim}{x}) \;. \tag{9}$$

Equation (8) is very powerful and elegant, although "beauty is in the eye of the beholder"! It expresses the retarded E1 current in terms of 3 physical quantities, $\vec{D},\vec{O}$, and $\vec{N}$ and satisfies current conservation without any approximation. The latter proof is left as an exercise. We also note that this form is unique in its maximal use of current conservation, because of our use of permutation symmetry with respect to the indices on the vectors. The form we have derived is the logical extension of Siegert's early work and is also different from others used commonly in the past. Although $\vec{D}$ and $\vec{O}$ have a simple structure, $\vec{N}$ requires a little work to develop for a single electron:

$$\vec{N} = -\frac{3\mu\vec{\sigma}\times\vec{r}}{2m} + \frac{e}{2m}\{\vec{r},\times\vec{L}\} + \ldots . \tag{10}$$

The two terms above arise from the spin-magnetization current and convection current, respectively. Additional currents, such as exchange currents, generate additional components of $\vec{N}$. Experts will note that the transverse (to $\hat{q}$) retardation correction in the Siegert term is 6 times smaller than the usual correction and that $\vec{N}$ doesn't involve the radial derivative present in the usual form!

After this short digression to develop a new multipole formula, we can investigate the size of various contributions to the $^3P_1 \to {}^1S_0$ atomic decay. As we remarked earlier, the spin-independent parts of $\vec{D}$ and $\vec{O}$ don't contribute to the direct triplet-singlet transition. The spin-orbit dipole operator does, and so does the spin-dependent term in $\vec{N}$: $\vec{N}_s$. We can easily compare the contributions of these two terms by using a trick. We use the fact that $q = \omega$, the photon energy, and also is the negative of the energy difference of atomic final and initial states: ω_{fi}. The approximate relationship $p=im[H,\vec{r}]$, where we ignore the relativistic corrections in H, then leads to

$$\vec{J}_{\perp}(q) \cong i\omega_{fi}\vec{D}_o + \frac{\omega_{fi}^2}{4m}((2\mu-e)-\mu)\vec{\sigma}\times\vec{r} . \tag{11}$$

Equation (11) displays the component of $\vec{J}$ orthogonal to $\hat{q}$ in terms of the Siegert part, as well as the spin-orbit term and the retarded magnetic correction, $\vec{N}_s$; it ignores $\vec{O}$ and the remaining parts of $\vec{N}$, which make negligible contributions. For electrons, the anomalous magnetic moment is tiny and thus $\mu \cong e$. Consequently, the spin-orbit and retarded spin terms cancel, and the spin-flip terms induced by the atomic spin-orbit forces drive the transition. The overall size of either of the cancelling terms[16] compared to the leading dipole term is roughly 25% for helium. The agreement between theory and experiment is quite good.[16,17]

The lessons learned above in the atomic physics examples are immediately applicable to nuclear physics. In order to "see" relativistic corrections in nuclei it is necessary to find physical situations where the dominant nonrelativistic contributions cancel. It is not feasible for us to perform measurements with incredible accuracy and reliably calculate and subtract the dominant nonrelativistic parts. Nobody would believe the result. Fortunately, a process exists which provides convincing evidence of special relativity at work in a nucleus. Figure 3 shows an electromagnetic wave (photon) impinging on a deuteron. The electric field vector of the photon is orthogonal to the Poynting vector and exerts a force on the proton in the same direction. This classical argument indicates that the protons are preferentially directed at right angles to the photon beam and are forbidden in the forward direction. At the bottom of the figure is depicted the unit angular momentum of the photon directed along the Poynting vector. The orbital angular momentum of the n-p system along this direction vanishes when the proton is forward-going. Ignoring the spins of the nucleons, the process must be forbidden!

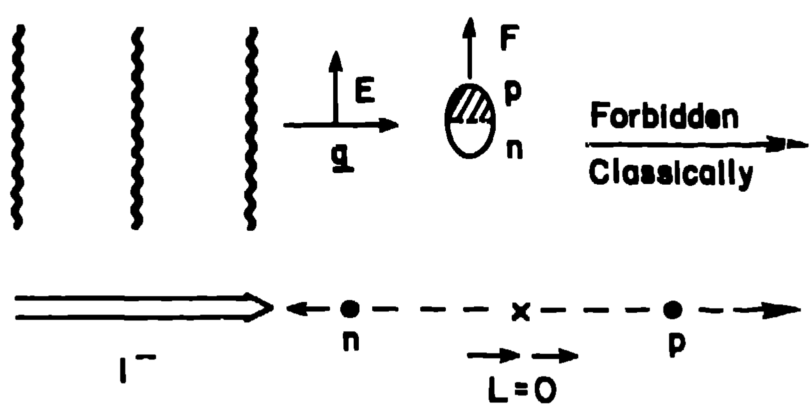

Fig. 3. Classical kinematics for deuteron forward photodisintegration.

The reaction is not forbidden, of course, but is greatly suppressed by the argument given above. In order to calculate the dominant electric dipole process accurately, we need to say a few more words about the Siegert form of the current operator. The classical component of the current is $e\vec{v}/c$, where $\vec{v}$ is the velocity of the particle whose charge is e. In a nucleus there are other, comparable currents arising from the flow of charged mesons. Roughly half of the mesons which are exchanged are charged and generate meson-exchange currents. Only the long-range parts of these currents are known. It is therefore absolutely necessary to use Siegert's theorem. In atomic physics these two currents are called the dipole-velocity and dipole-length forms. Only the latter has any fundamentality when the Hamiltonian contains relativistic corrections, as it did in our example earlier. Deuteron photodisintegration for 90° protons is shown in Figure 4, calculated in the unretarded electric dipole approximation using the length (Siegert) and velocity (convection) current forms. The large difference is the effect of interaction currents included implicitly in the former. According to Professor Arenhövel,[18] these effects are largest for the E1 multipole and become progressively smaller as the multipolarity increases.

We will see later that the 0° electric dipole cross section is approximately 2 μb for 10 MeV photons. This is an enormous suppression, which we predicted, but is nonvanishing. What physical ingredients drive the forward reaction? We have ignored the nucleon spins that drive the M1 amplitudes; these are primarily spin-flip in nature. We have also ignored the intrinsic spin-dependent effects in the wave functions, particularly in the deuteron ground state whose D-wave component is the result of noncentral forces. We can categorize the ingredients for a nonvanishing cross-section as follows:

(1) Noncentral forces between the nucleons in the excited state;
(2) The deuteron D-state, resulting from noncentral forces;
(3) Spin-dependent transition operators;
(4) Possib' exotic phenomena of non-nucleonic nature.

We see that with the exception of category (4), the situation is identical to that of our previous example, the $^3P_1 \rightarrow {}^1S_0$ radiative decay. The spin-independent dipole operator $\vec{D}_0$ contributes only in the presence of noncentral forces. The spin-orbit dipole operator[19] $\Delta\vec{D}_{so}$ and spin-current[20] $\vec{N}_s$ also should make large fractional contributions. The only change in the analysis following eqn. (11) reflects the large isovector magnetic moment of the nucleon: 4.7 n.m. The electric dipole reaction proceeds primarily to ^3P_J excited states, which have isospin 1. The isospin change requires μ_v in all operators; we consequently can neglect e compared to μ in eqn. (11). The spin-orbit contribution should therefore be roughly twice that of $\vec{N}_s$, and opposite in sign.

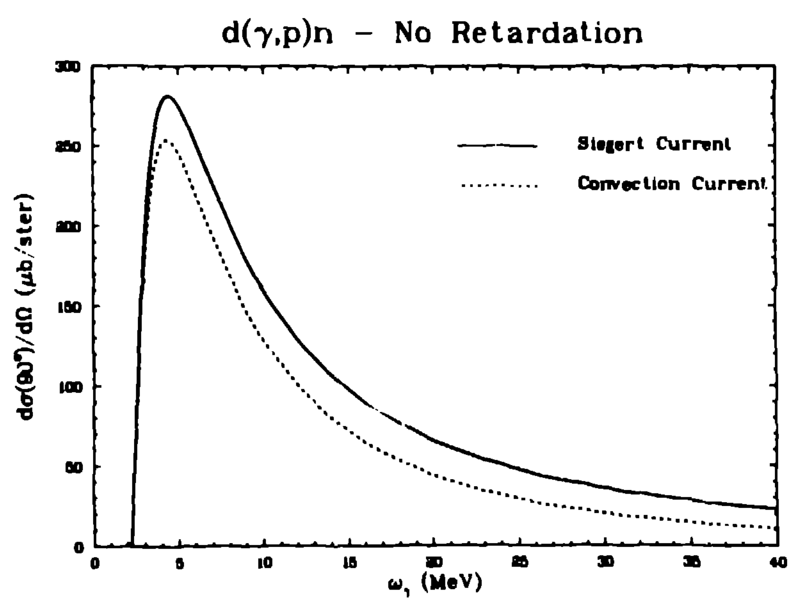

Fig. 4. Siegert and classical contributions to photodisintegration.

Figure 5 displays the percentage contributions of the $\vec{O}$ and $\vec{N}$ retardation corrections to the Siegert term at 0°. Both old (i.e. conventional) and new (eqn. 8) forms are shown. Note that $\vec{O}$ is smaller by a factor of 6 in the new form, and the orbital part of $\vec{N}$ ($\vec{N}_o$) is also smaller, in general. The spin part of $\vec{N}$ is the same in both forms and is approximately a 10% effect for photon energies near 100

MeV. The contribution of the usual pion-exchange currents to $\vec{N}$ ($\vec{N}_{ex}$) is quite small in the new form. The +10% estimate for $\vec{N}_s$ indicates that $\Delta\vec{D}_{so}$ should generate a -20% contribution.

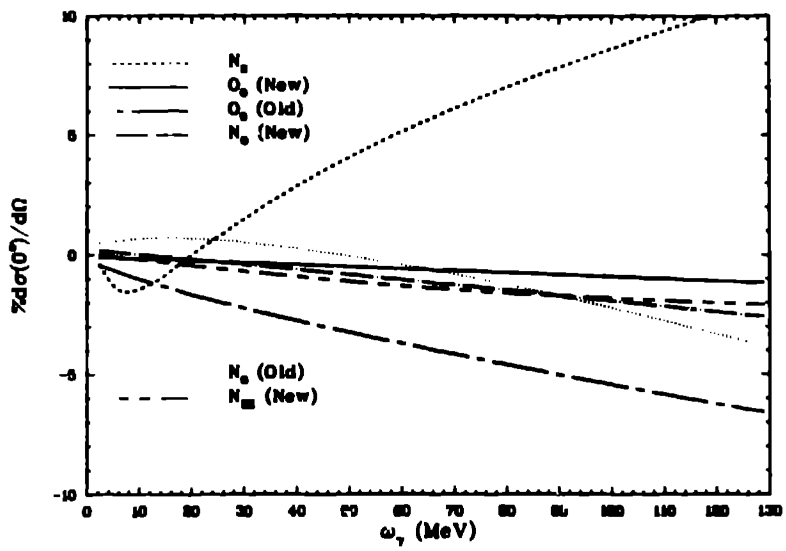

Fig. 5. E1 retardation corrections.

In order to produce a quantitatively accurate calculation of cross-sections, it is necessary to include higher multipoles. The contributions through L=2 are shown in figure 6. The anomalously large contribution of M2 is caused by the dominance of this isovector spin-triplet multipole by the spin-magnetization current and its very large μ_v. Higher multipoles are much smaller.

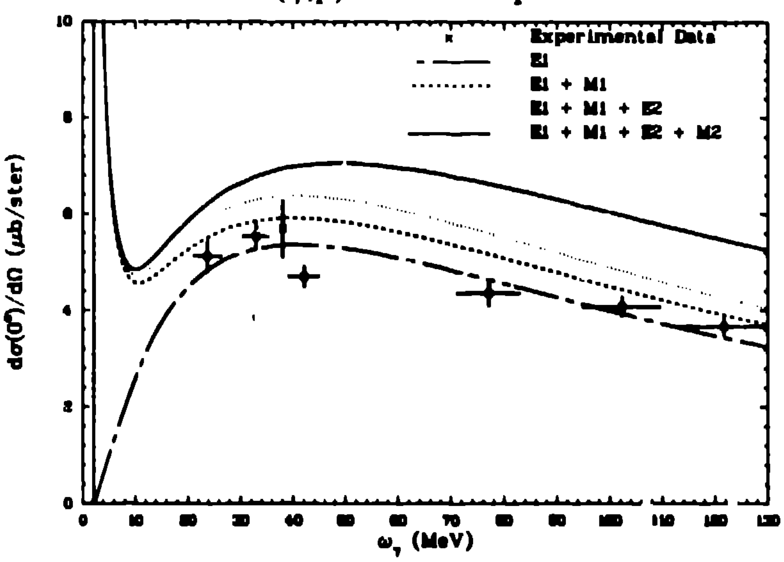

Fig. 6. Multipole contributions to deuteron photodisintegration.

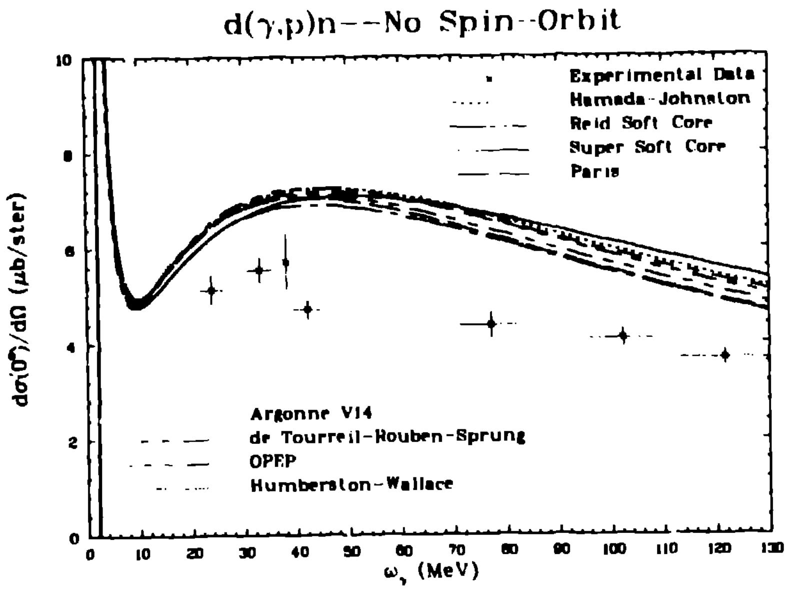

Fig. 7. Photodisintegration for various potential models.

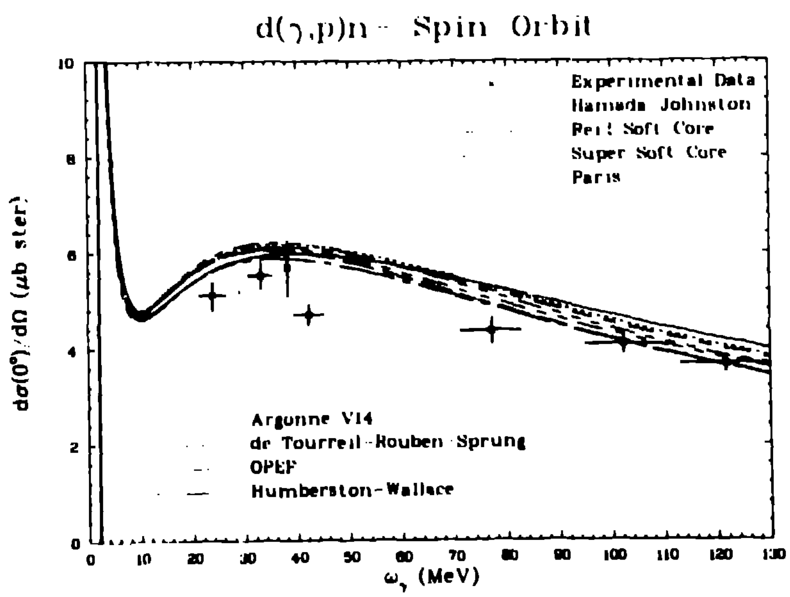

Fig. 8. Photodisintegration including spin-orbit operator.

In order to make a convincing case that the spin-orbit dipole operator eliminates most of the discrepancy between nonrelativistic impulse approximation and the experimental data,[21,22] we have calculated the former using 8 "realistic" potential models.[23] All lie close together in Figure 7, as do the corresponding spin-orbit results in Figure 8. In fact, the spread in the curve is illusory. The use of Siegert's theorem results in the process being dominated by factors of r^L and hence by the tails of the wave functions. Figure 9 shows what happens when the deuteron D-state is turned off: most of the cross section vanishes. It is therefore appropriate[24] to correlate the cross section with the deuteron asymptotic D-state normalization parameter: $A_D \equiv \eta A_S$. Scaling the curves in Fig. (7) to the experimental value (.024) of A_D produces Fig. (10). The grouping is much tighter except for the Hamada-Johnston and Reid Soft Core potentials. The latter has poor P-wave forces, while the former has an incorrect deuteron binding energy. The Humberston-Wallace modification of the HJ potential does not have that defect. The correct inclusion of forces in the excited states is quite important. The dotted curve in Figure 9 neglects such forces. Even the inclusion of the J=3 forces in the RSC potential isn't a negligible effect. Those forces, developed but not published by Reid, were recently published by Day.[25]

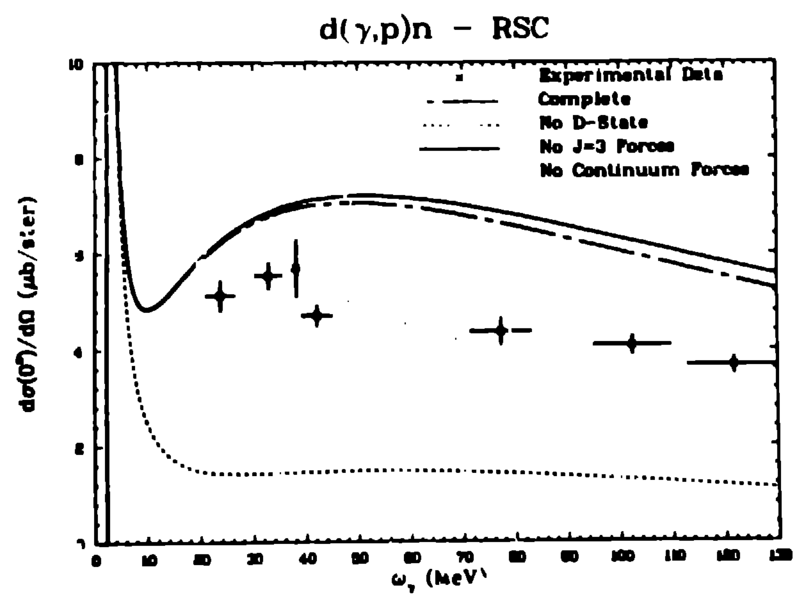

Fig. 9. Limiting cases for photodisintegration with RSC interaction.

The pion clouds around the nucleons contribute to the nuclear charge density via fluctuations, a kind of induced zitterbewegung. Just as the Lamb shift can be viewed as a "smearing" of the electron's charge by recoil when a virtual photon is emitted and absorbed, so do the nucleons recoil and modify the density while exchanging pions. The resulting charge density modification is spin-dependent, because the formation of the pion cloud is correlated with the nucleon spins. Consequently, a spin-dependent pion-exchange dipole operator is created in the deuteron, and can play a role in photodisintegration.

We show in Fig. 11 the consequences of including $\Delta\vec{D}_\pi$, the pion-exchange part of the electric dipole operator. This operator suffers a two-fold unitary ambiguity,[26] determined by parameters μ and ν. The parameter μ determines the equivalence representation, which relates in appropriate fashion the pseudoscalar (PS) and pseudovector (PV) types of pion-nucleon couplings. The parameter ν determines how retardation in the exchange is handled. In our discussion of the $^3P_1 \to {}^1S_0$ decay we did not mention any contribution to $\vec{D}$ from photon exchange. Such a contribution is possible, but doesn't occur because all atomic physics calculations involving photon exchange are performed in Coulomb gauge.[2] This gauge is equivalent to $\nu=1$ (the "soft" representation) and eliminates such terms. For photon and scalar- or vector-meson exchange[14] this representation eliminates to order $(v/c)^2$ the isoscalar part of the exchange charge density, $\Delta\rho_V$.

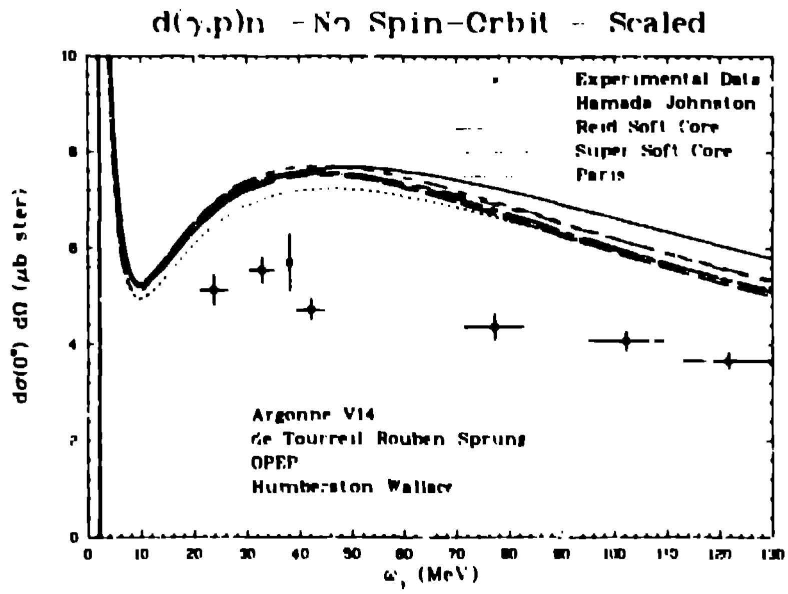

Fig. 10 Scaled photodisintegration for various potential models.

It is conventional to use PS-coupling in calculating $\Delta\vec{D}_\pi$. This is inappropriate. Threshold pion photoproduction from the nucleon is a good test of Born-term models. Neutral pion photoproduction is very different for the PS- and PV-cases, and experiments support the latter,[27] which is consistent with current algebra. One should therefore not use PS-coupling. The PV-case is trivially obtained from the PS-results by replacing nucleon magnetic moments by 1. Results for PS-coupling are the top two curves in Fig. 11, showing the complete and local approximations for a specific, common representation. Most calculations implicitly use $\mu=-1$ and drop momentum factors. That case for PV-coupling is shown next and is only about half of the corresponding PS-case. Three other representations are also shown, as well as the comparison curve which includes $\vec{N}_{ex}$ and exchange contributions to the magnetic dipole process, but not $\Delta\vec{D}_\pi$. The former contributions are nonrelativistic and independent of the specific coupling scheme. Note that all the PV-cases are reasonably consistent with $\Delta(d\sigma/d\Omega)_\pi = (2\nu-\mu-1)\ X/2$ with $X>0$. Thus, choosing $2\nu-\mu-1=0$ corresponds roughly to impulse approximation. For isoscalar processes,[26] $\Delta\rho_\pi$ vanishes for $\nu=1$, $\mu=3$. All these calculations are inconsistent, of course. The matrix elements in a consistent calculation would be independent of μ and ν, the wave functions changing in each case to accomodate the different operators, $\Delta\vec{D}_\pi$. Unfortunately, the commonly used realistic potential models don't correspond to <u>any</u> of the representations we have discussed.

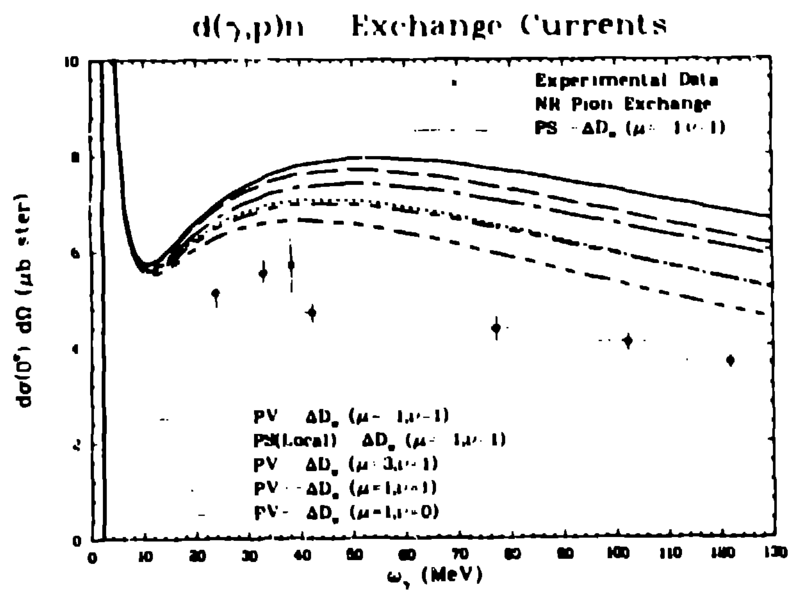

Fig. 11. Photodisintegration including pion-exchange dipole operators.

In conclusion, we have calculated deuteron forward photodisintegration and shown that it is the analogue of the $^3P_1$-$^1S_0$ radiative decay of helium-like ions. The latter process vanishes unless terms of order $(v/c)^2$ are calculated; in our opinion, the former process is the first convincing case of a relativistic correction in a nuclear process. We have also developed the extension of Siegert's theorem for nonvanishing wave lengths;[28] alternative forms have no compelling features and should not be used for electric transitions. All of our examples of relativity at work involve the spin-orbit interaction in various ways. Finally, we have seen how interaction-dependent operators of relativistic order are ambiguous; a definitive calculation using $\Delta\vec{D}_\pi$ remains to be performed.

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